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E-Plane Five-Port Two-Way Waveguide Power Divider/Combiner with High Amplitude and Phase Consistency

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Abstract—This paper proposes a compact E-plane five-port waveguide power combining and splitting structure in the V-band. The symmetrical five-port structure guarantees excellent amplitude and phase consistency between the input/output ports. Two isolation ports guarantee high isolation between the input/output ports. Meanwhile, the E-plane waveguide structure is more compact than H-plane structure. A two-way power combing structure working from 59 GHz to 64 GHz is designed, fabricated and measured for validating our structure. The measured results show that the phase and amplitude differences between the input ports are smaller than ± 1.0 degree and ± 0.1 dB, isolation between the input ports higher than 18 dB, insertion loss and return loss lower than 0.2 dB and better than 17 dB, respectively.

1. INTRODUCTION

A power splitting and combining structure is an essential part in a millimeter-wave system. Good transmission loss, low input/output ports VSWR, excellent amplitude and phase consistency and isolation between input/output ports, easy fabrication and compact structure are all what we expect in a power combining and splitting structure [1–3]. In [4–7], H-plane waveguide power dividers/combiners are proposed. In [4] and [5], a waveguide narrow wall (H-plane) Reblit coupler is proposed in the W-band and Ku-band. The Reblit coupler has 90° phase error between the output ports. In [6, 7], a novel five-port H-plane waveguide divider is proposed. In [8], a six-port H-plane waveguide divider is proposed. Compared with H-plane, the E-plane waveguide power divider and combiner can realize device and networks miniaturization because of the characteristic of waveguide. A four-way E-plane Y-junction power dividing/combining network is proposed in [9]. However, it improves ports isolation by using one vertical resistive card and two horizontal resistive cards, which increase the complexity of assembly and fabrication. In [10], a 4-branch waveguide equal power divider is proposed. It is based on a Y-junction structure and optimizes the branch angle to realize power equal division. It has no port isolation between the four output ports. In [11, 12], a three-dimensional power dividing/combining structure, such as Magic-T power divider, is proposed. However, the three-dimensional structure increases the difficulty of fabrication and assembly in the project.

In this paper, we propose a compact five-port waveguide power combining structure with high phase and amplitude consistency in the V-band. The proposed structure possesses excellent amplitude and phase consistency and high isolation between input ports. Meanwhile, compact size, easy fabrication and assembly structure guarantees the device performance in the high frequency band, such as V-band, E-band and higher.

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2. THE CONFIGURATION OF THE PROPOSED STRUCTURE AND ITS MECHANISM

An E-plane five-port waveguide power combining structure is proposed in Figure 1 and Figure 2. The structure has five ports: two input ports, two isolated ports and one output port. It includes three waveguide sections along the wave transmission direction in the whole structure: the output and isolated ports in region I, the power coupling and combining region in region II and the input ports in region III. Region I is composed of three adjacent waveguides: one is used to output the combining power from the input ports, and both sides are used to improve the isolation between the two input ports. There is a common coupling section to realize input power coupling at region II. In the coupling and combining region, waveguide with E-plane steps and two symmetrical metal cylinders inserted into coupling regions are used to realize wide operation bandwidth and structure miniaturization [13].

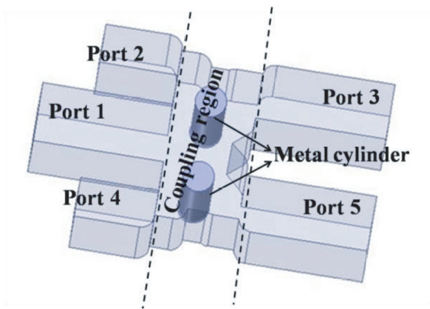


Figure 1. The configuration of the proposed E-plane five-port waveguide power combiner.

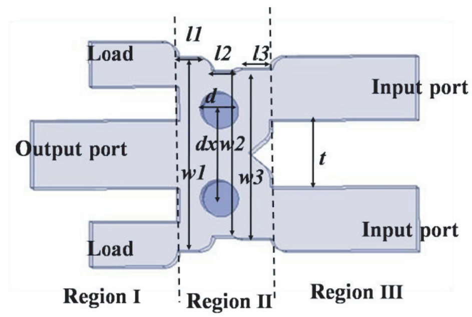


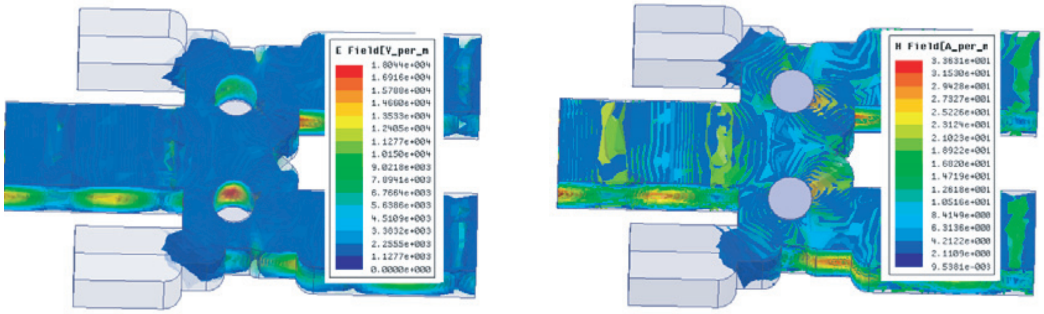
Figure 2. The flat-screen graphic of the designed power combiner.

This structure realizes power combining by the waveguide E-plane common wall between the three adjacent waveguides in region II. The symmetrical structure along the longitudinal axis guarantees excellent amplitude and phase difference. The two isolated ports in region I improve the isolation between the two input ports by absorbing any mismatching input port power. The E-plane waveguide structure guarantees the structure miniaturization.

Meanwhile, in high frequency band, the amplifier chip or module power combining is based on the E-plane waveguide-microstrip structure, which is the most popular one used in the chip integrated power combing structure to realize compact size. The proposed E-plane power combing and splitting structure is the first choice in the system integration.

The classical waveguide power divider is an H-plane structure, which realizes power coupling and splitting by the narrow wall [13, 14]. The electromagnetic wave coupling depends on the phase difference between the TE10, TE20, TE30 and other modes propagating through the common coupling region. The bigger waveguide wide wall results in the appearance of higher-order modes. However, the wide wall value of E-plane waveguide combiner is consistent. So, when TE10 mode is input from the input ports, in the output port and power coupling region, only TE10 mode exists. When TE10 mode is input from the two input ports, the length ($L = l1 + l2 + l3$) of coupling region II and two symmetrical metal cylinders decide power combining efficiency. When the electromagnetic wave is input from the input ports and transmits into the coupling region, the characteristics of E- and H-fields in the waveguide compel the electromagnetic wave to change field distribution and output from the output port.

Figure 3 shows electric and magnetic field distributions of the proposed combiner by the HFSS simulation software. The two input ports electromagnetic waves in the coupling region realize power combining mainly by electromagnetic field coupling. In region II, the public area between region 1 and region 3 becomes wider for the waveguide wide wall. The wide-wall "a" of standard waveguide is certain for electromagnetic wave propagation. When the value of wide-wall "a" is altered to become wider, the other higher transition modes will be simulated and exist with the fundamental mode TE10. The higher transition modes and fundamental mode will affect electromagnetic wave propagation characteristic and realize power combining in the common combining region II. The two metal cylinders increase the coupling intensity and reduce the volume of the coupling region.



(a) (b)

Figure 3. (a) Electric field distribution and (b) magnetic field distribution within the combiner.

3. DESIGN OF THE PROPOSED POWER COMBINER

A two-way E-plane waveguide power combining structure in the V-band is designed. At design stage, we use full-wave simulation tools HFSS to determine the whole structure needed parameters value, and optimize it to achieve the best performance in the 59–64 GHz band. The values of all the parameters after being optimized in the software are shown in Table 1. The input and output waveguides are designed as WR-15 standard waveguide: $a = 3.76$ mm, $b = 1.88$ mm. In the simulation software, the two isolated ports are designed as port 2 and port 4 as shown in Figure 2. That is because the simulation speed is very low if it is designed as matching load. Meanwhile, the port setting and the function of matching load with absorbing material are the same. In [15], the return loss of matching load can be achieved better than 20 dB in a broad operating band. So the leaked power coming from the input ports by mismatch or other reasons can be absorbed completely.

Table 1. The values of all the parameters of the structure.

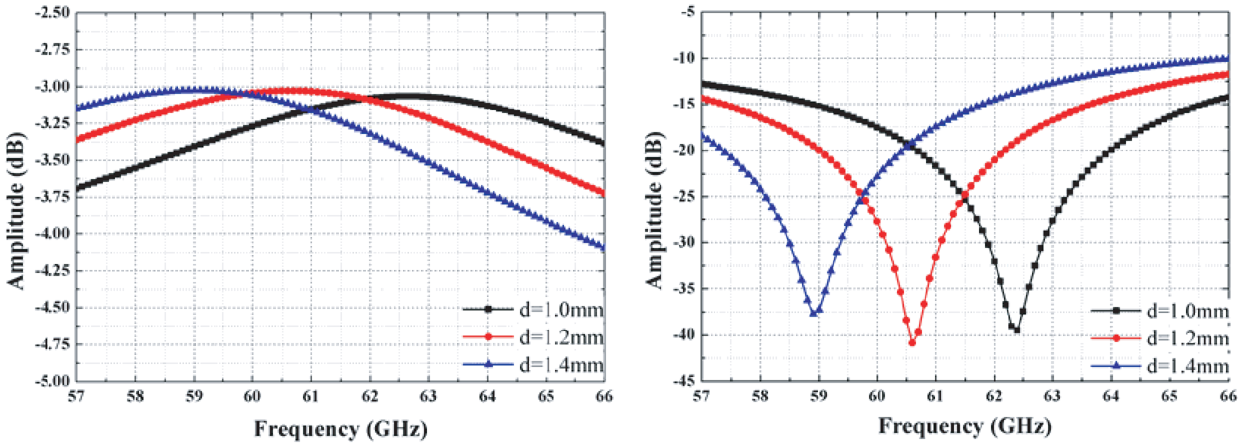
parameter	Value (mm)	parameter	Value (mm)
$l1$	1.1	$w2$	5.6
$l2$	0.7	$w3$	5.9
$l3$	1.2	d	1
$w1$	6.6	dx	3

In the millimeter-wave frequency band, such as V-band, W-band and higher, the operating frequency band offset because of fabrication and assembly error is an important factor in the design. In the high frequency band, it is impossible to tune working frequency with screw. So, in the design and simulation process, we can find a few sensitive parameters, such as the shape (d) of the two metal cylinders, to simulate its tolerance and improve the fabrication accuracy.

In the software simulation, we find that the working frequency band is sensitive for the two metal cylinders' shape (d). A little simulation and fabrication error will result in a relative bigger frequency offset. Its influence can be found by the insertion loss (S_{31} and S_{51}) and isolation between the input port and isolated port (S_{21} and S_{41}). Figure 4 shows the influence of parameter tolerance of d on S_{21} and S_{31}. We choose a middle optimum value and reserve ± 0.1 mm fabrication accuracy to guarantee the working frequency band in the needed band. Figure 5 shows the simulated results after all the parameters are optimized in the HFSS. The values of all the parameters are shown in Table 1.

4. MEASUREMENT OF THE PROPOSED TWO-WAY POWER COMBINER AND DISCUSSION

The simulated two-way five-port E-plane power combiner is fabricated and measured. As in [15], if the wedged absorbing material is placed into the two isolation ports, its function is the same as the



(a) (b)

Figure 4. The simulated results of insertion loss (a) S_{31} and (b) S_{21} by the parameter tolerance of d.

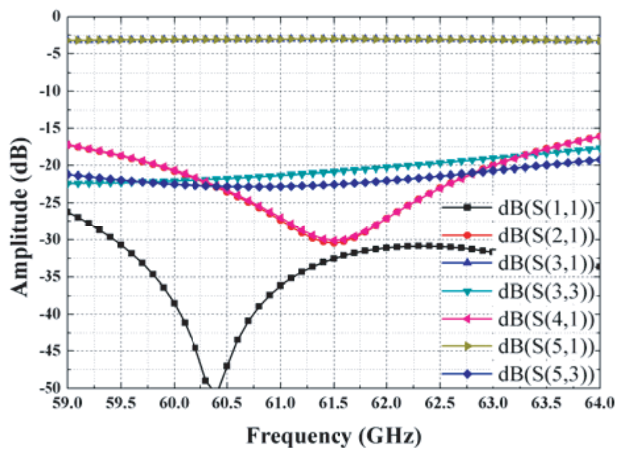


Figure 5. The optimized simulated results based on the parameter value of Table 1.

waveguide load. Good return loss can be achieved to better than 20 dB in a broad operating band in [15]. Figure 6 shows photographs of the fabricated two-way waveguide power combiner, with a small fabrication dimension 40 mm * 20 mm * 20 mm.

Figure 7 and Figure 8 show the simulated and measured results of the fabricated two-way waveguide power combiner. In 59–64 GHz, the tested results indicate that the transmission loss is lower than 0.2 dB, the amplitude and phase imbalance between the two input ports better than ±0.1 dB and ±1.0 degrees, the isolation between the input ports higher than 17 dB, and the return loss of the input/output ports better than 17 dB. The measured results are in good agreements with simulated ones which verifies the good performance of the proposed structure. The high amplitude and phase consistence, isolation between the input/output ports, and low insertion loss guarantee the high combing efficiency as a power divider and combiner.

Table 2 demonstrates the comparison of the designed V-band E-plane waveguide power combiner with the reported references, from which we can find that the high phase and amplitude consistency between the output ports, isolation between the input/output ports without adding the difficulty of the fabrication and assembly, and the E-plane compact waveguide power combiner proposed by our group are better than the others.

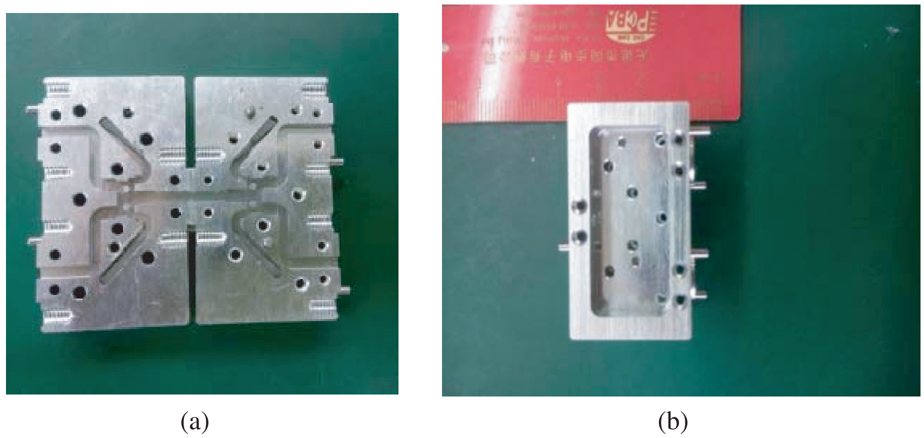


Figure 6. (a) The assembly photograph and (b) the overview photograph of the fabricated combining structure.

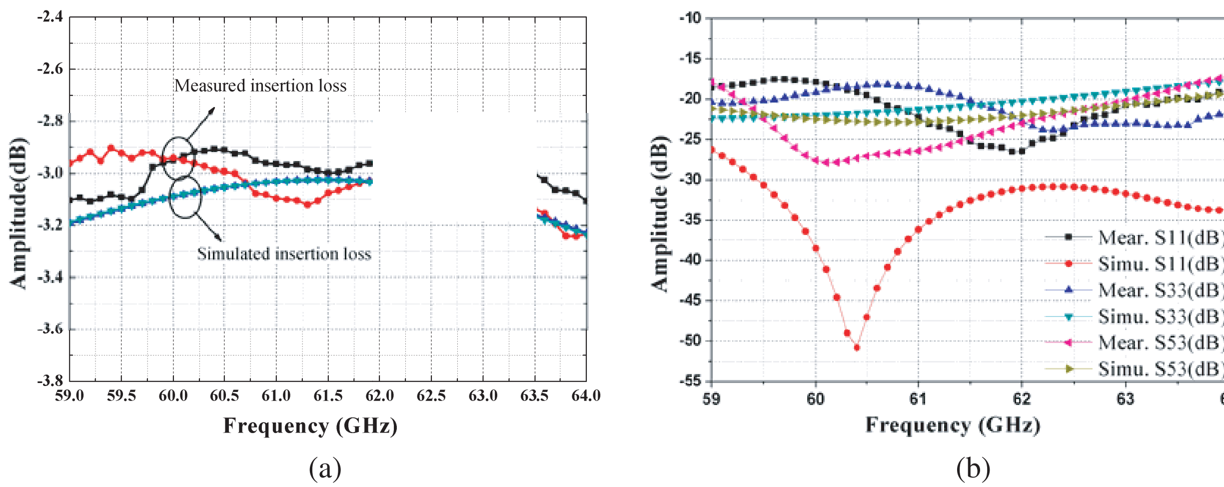


Figure 7. The (a) measured and simulated insertion loss and (b) port return loss/isolation.

Table 2. Comparison of proposed structure and conventional structures.

Paper/This work	Ref. [4]	Ref. [5]	Ref. [7]	This work
Frequency (GHz)	29–37	8–11	31–35	59–64
Structure	E-plane	E-plane	H-plane	E-plane
Isolation (dB)	> 11	good	> 18	> 17
The differential phase (degree)	–	–	± 1.5	± 1
Imbalance of the amplitude (dB)	–	–	± 0.1	± 0.1
Fabrication and assembly	difficult	difficult	easy	easy

5. VERIFICATION OF THE PROPOSED POWER COMBING STRUCTURE

The good performance of passive power combining structure guarantees high power combing efficiency in the system. The low insertion loss makes the combined power loss lower. The high amplitude and phase consistency between the input ports or output ports makes the power signal good in-phase combining, and the high isolation between the input ports reduces the power cancelation interference because of

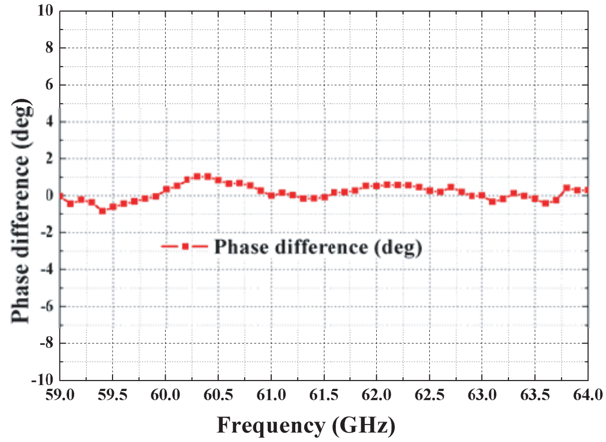


Figure 8. The measured phase difference between two input ports.

Figure 9. The power combining power amplifier structure.

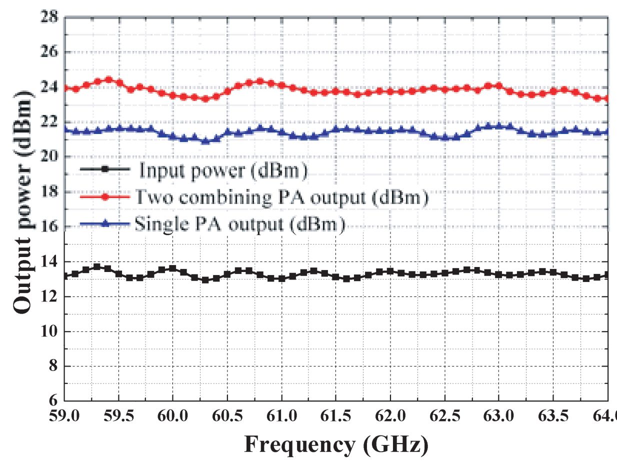


Figure 10. The measured results of power combining power amplifier structure.

the bad return loss of active amplifier. The compact structure guarantees the system miniaturization.

To verify the combining efficiency of the proposed structure, two measured power amplifiers and two proposed structures are assembled together as shown in Figure 9. The gain and phase of the two power amplifiers are nearly the same. They are measured in the Vector Network Analyzer. Figure 10 shows the measured results based on the amplifier structure. The signal is input from the power divider, amplifier module and output from power combiner. The measured results show that the output power is 2 dB greater than single PA output power. The excellent isolation and good amplitude and phase consistency between input/output ports guarantee the high combining efficiency greater than 95%, which is the best certification of this proposed high-efficiency power combining structure.

6. CONCLUSION

A compact E-plane five-port waveguide power combining structure is proposed. The E-plane waveguide power combining structure can achieve excellent phase and amplitude consistency because of its symmetry and good input/output port isolation by two isolation ports. The excellent phase and amplitude consistency guarantees the high power combining efficiency in the power combining system. A two-way E-plane waveguide power combining structure is designed, fabricated and measured. The measured results verify the good performance of the proposed power combining structure.

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